V. Photomultiplier Tube System.

Two types of photomultipliers will be used to read out the EMC barrel. The 30 mm single channel PMT FEU115M[1] will be used to read out the 21 fibers coupled to the 21 scintillating tiles in the calorimeter towers. 4800 of these PMTs will be required to readout the entire barrel calorimeter. In addition 300 R5900U[2] 16-channel, multianode PMTs will be used to readout the preshower signals from each tower. In what follows the details of the PMT system will be discussed.

V.1 PMT Specifications

Table 1 shows a partial list of our requirements for the main barrel PMT and the technical justification for each item.

Item	Description	Requirement	Technical Justification
1	Pulse linearity	better than ± 1% between 0- 25 mA peak current @ $g=1\times10^5$	upper limit imposed by loss of linearity in the barrel due to leakage of energy at 60 GeV
2	Dark Current	less than 5nA at a gain of $g=4\times10^5$ at 25° C.	limit imposed by source calibration system. The contribution of the dark current to the total integrated charge to be 40-50 times lower than that of a 1 mCi ^{60}Co source.
3	Photocathode uniformity	better than 10% over a circular spot of diameter 10 mm for all PMTs	limit imposed by requirement to sample 21 layers of a tower uniformly. This will be done by using a diffuser to couple the fiber bundles to the PMTs.
4	Quantum effic.	better than 12.5% @ 490 nm for all PMTs.	to minimize the contribution of the photostatistics compared to intrinsic EMC sampling limits. (Ref. STAR note SN0316)
5	gain	at least 4×10^5 @ -1800 V[3] for all tubes within ΔV=200 volts	required to fit the largest signals (i.e., 60 GeV @ η = 1 deposits ≈ 900pC in the ADC) in the high end of 14 bit dynamic range of the ADCs with least significant bit resolution of 0.25 pC (12 bit resolution + pedestal).
6	rise time/ (transit time)	not to exceed 4 ns/ (less than 40 ns for a 10 mm diameter spot centered on the photocathode) @	to avoid nonlinearity caused by space charge density buildup due to high inst. rate.

[1] Made by MELZ at Russia.
[2] Made by Hamamatsu Corp.
[3] Measured with voltage division ratio (K-A): 3R, 2R, R, R, R, R, R, R, 1.2R, 1.6R, 2R, 3R, 3R.

		1800 V with thitered[3] PMT base.	
7	useful life	all specs. remain within required limits for anode integrated charge of 10C	10 years lifetime for the detector. (37 week operation/year with 5KHz signal/tower at 166 p.e./MIP g = 4×10^5)

Table 1. Specifications for STAR barrel EMC photomultiplier tubes.

In addition to the specifications listed in Table 1 we require that the PMTs meet the following stability criteria:

Item	Description	Requirement
1	short term gain stability	after burn in at 5 µA for 40 hours stable to 1% for 100 hours @ 2 µA @ 25°C
2	long term gain stability	after burn in at 5 µA for 40 hours stable to 2% for 1000 hours @ 5 nA @ 25°C
3	Temperature dependence	Quantum efficiency change of less than 0.5%/°C
4	Rate effects	<5% change in gain for current change from 5 nA to 2 µA. <1.5% change in gain for current change from 5 nA to 500 nA.
5	pulse recovery	gain must recover to within 2% within 1 msec after 25 mA peak pulse.
6	dark current stability	<10% change @ 25°C over time after initial burnin period.

Table 2. Stability requirements for the STAR barrel EMC photomultiplier tubes.

The FEU115M manufactured by MELZ sufficiently meets[4,5,6,7,8] the requirements outlined above. Figure 1 shows the gain of the FEU115M as a function of applied HV with the MELZ PMT base.

[4] "Study of a FEU-115M Photomultiplier", S. Majewski et al. CEBAF internal note 6/12/93
[5] "Study of a FEU-115M Photomultiplier Part II", S. Majewski et al CEBAF internal note 6/25/93
[6] "Study of a FEU-115M Photomultiplier Part III", S. Majewski , CEBAF internal note 7/22/93
[7] "Performance Studies of A New Russian FEU115M Phototube", G. David et al PHENIX EMC notes.
[8] "FEU115: tests of rate effects at low frequencies", G. David and A. Patwa, PHENIX EMC notes.

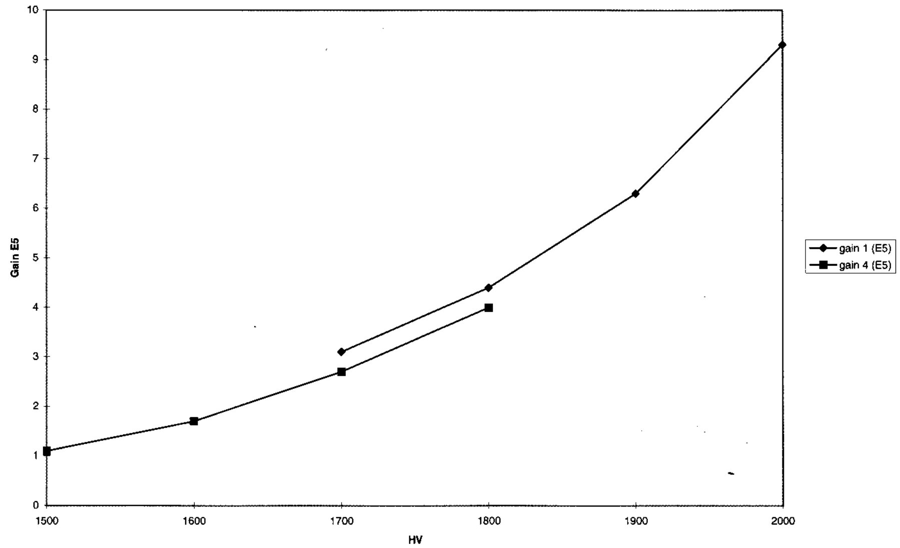

Figure 1. Measurement of the gain vs. HV for FEU115M.

In order to readout the preshower signals Hamamatsu R5900 16 channel multianode PMTs are chosen. The choice of this PMT is based on space limitations as well as cost issues. The CDF collaboration has made in depth[9] studies of R5900 for their shower max detector. Of particular interest is the cross talk between neighboring channels, and channel to channel gain variations of factor 3. Further studies on these PMTs will be required.

V.2 PMT base design.

Unlike the PHENIX EMC modules where the PMTs are geometrically arranged in close proximity, which allows one to combine the HV distribution and control functions of several PMTs into a single module, the PMTs in STAR barrel EMC are uniformly distributed over the iron return backlegs, in light tight boxes over the entire surface of the detector. As such they pose a safety as well as integration problem for traditional HV systems where each PMT would require a HV transmission line.

In order to minimize power dissipation, cost, and address the safety concerns associated with distribution of HV for a large number of PMTs it was decided, right from onset of the EMC project that a Cockcroft Walton type base would be most appropriate for the STAR EMC.

In addition to safety and cost issues CW bases have advantages over traditional resistive divider bases since they dissipate less heat and provide better transient response due to lower impedance.

The operation of a CW PMT base has been described by several authors, suffice it to say that in general a CW base consists of a charge pump, a diode/capacitor multiplication chain, a voltage reference, a feedback loop and a mechanism to regulate the output voltage by comparing a fraction of the output voltage with the reference voltage (usually supplied

[9] “Preliminary results of tests performed on Hamamatsu R5900 ...”, M.Lindgren et al., 8/3/1995, CDF report.

by a DAC). Care must be taken to decouple switching induced noises from the PMT anode signals. Experience with the RICE design and other CW designs shows that this can be done by careful PCB layout and proper shielding by providing low impedance ground planes. Since the temperature in the PMT boxes is controlled then the variations of the HV usually associated with the drift of reference voltages may be ignored.

In our design we use a pulse width modulation/pulse frequency modulation system to regulate the HV on the CW chain. Only 12 volt and 5 volt DC external supplies are required. The base develops pulses of 0-100 volt which, when applied to the CW multiplier chain will develop dynode voltages according to the division ratios defined by the number of multiplication stages. One such base has already been developed for STAR CTB by Bonner Lab. The Bonner design is developed to operate in the 0.5 T magnetic field of STAR as such it uses no magnetic materials and is rather bulky. Our design will utilize small inductors in buck-boost configuration driven by a P-channel MOSFET controlled by a PWM/PFM DC converter chip.

The work on this is at the prototyping stage. We estimate the cost per unit of approximately $75. This includes the cost of a 12 bit DAC per base. Note that in order to minimize gain fluctuations due to variations in HV one needs to have HV stability and resolution of better than 0.5 volt. This requires DAC s with better than 10 bit resolution. The commercially available DACs to fit this requirement have 12 bit resolution.

Figure 2 represents a conceptual design of a slow control system for the CW bases. A main interface module located on the EMC slow control crate will send the address and data bits via a differential bus (i.e., RS485) to multiplexer/demultiplexer modules located in the FEE crates, which in turn will address up to 80 PMT bases. This scheme requires each base to have a dedicated DAC, and ADC. As such it is more costly but more reliable since once a DAC’s register is loaded and enabled the CW may operate independently.

A second scheme developed by L. Hubbeling et al.[10] [11] for CERN experiment WA98 uses a single DAC to set voltages on up to 2000 PMTs. In this scheme each PMT base contains a sample and hold amplifier which when addressed by the DAC stores the value of the reference voltage. The trick is to refresh the sample and hold fast enough to avoid the sagging of the reference voltage by one LSB. In this scheme one saves the cost of the DAC; however, since the bases must be constantly addressed one produces a noisy environment in the CW base. Furthermore, if a controller card malfunctions, one will lose the ability to control the HV for a large number of PMTs.

[10] “Large Photomultiplier Systems- A New Approach”, L. Hubbeling CERN/ECP 92-10, 2 September 1992

[11] “HVOC, A VME High-Voltage Control Card for Large Photomultiplier Systems”, T. Hubbeling and L. Hubbeling CERN/ECP 93-2 15 May 1993

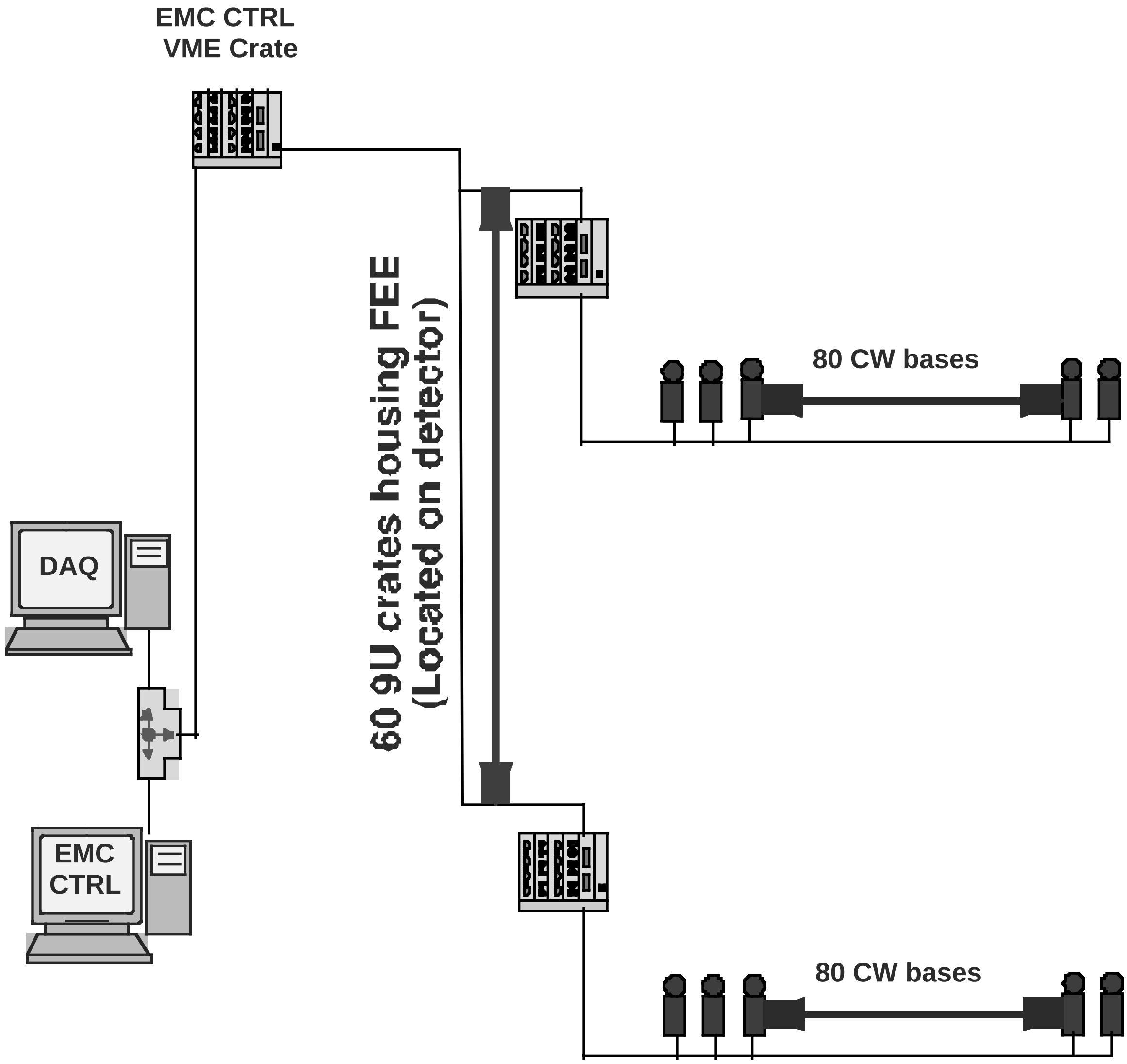

Figure 2. Conceptual design of PMT HV Slow control system.

A third scheme is to use the HDLC link[12] already present at the FEE crates for programming FEE modules, to program HVs for the PMTs. We are currently evaluating all of these schemes.

V.3 Quality Control and PMT Testing

The FEE115M PMTs purchased from MELZ will undergo factory tests before shipping. These tests will include an initial burn in test described in table 2. During this test the gain, quantum efficiency, dark current, and rise time of each PMT will be measured. Only those PMTs that meet the requirements for these tests will be shipped to US for further testing.

The Rochester University has the responsibility for testing the PMTs. The testing of the 4800 PMTs will be extended over a period of two years. During these tests the PMTs will be carefully tested and characterized. The criteria for testing the Hamamatsu R5900

[12] "The STAR TPC FEE HDLC Link", Paule Barale et al., LBL internal note, June 22, 1995.

PMTs is similar with the additional requirement that channel to channel gain variation and channel gain maps will be measured at the factory.

V.4 PMT assembly, PMT Box design and Integration

As mentioned earlier the barrel PMTs will be installed in light tight boxes installed on the magnet Iron backlegs. Each backleg Iron will support two boxes. Each box will house 80 FEU115M PMTs and five R5900U PMTs. Due to lack of 3D calculations of the magnetic field; there is a large uncertainty as to what the magnetic fields are on the Iron backleg along the entire length of the STAR. Some estimates put the field values anywhere from a few gauss to 100 Gauss. Therefore it is essential to protect the PMTs against stray magnetic fields. The PMTs will be wrapped with a layer of aluminum foil, which will be biased to the photocathode potential. This layer will be covered with insulating tape. A 1 mm thick μ-metal shield (ADVANCE Magnetics AD-MU-80) will be used to protect the PMTs against low magnetic fields. A 0.125" thickness soft iron shield will be used to attenuate intermediate magnetic fields down to low levels to prevent saturation of μ-metal shield.

In order to verify the shielding effectiveness of the PMT assembly we positioned it between the coils of a calibrated Helmholtz electro magnet (either in longitudinal or in transverse directions). By controlling the current in the coil one could set the magnetic field with an accuracy of better than 1%. A pulser was used to pulse a fast green LED[13] at 600 Hz with square 30ns ≈2 volt pulses. The LED was optically coupled to a FEU115M. The HV on FEU115M was set to -1800 volts (with factory supplied resistive divider base). The PMT outputs were sent to a fast digital scope (50 Ω termination) which was set to average a train of 500 pulses. The area under the averaged pulse was integrated to give the position of the peak of the pulse height distribution of LED signals.

Figure 3 and 4 show the shielding effectiveness of the PMT assembly for the transverse and longitudinal configurations, respectively. All amplitudes are normalized to zero field values. Note that the μ-metal shield alone is capable of shielding transverse fields of up to 100 gauss. However, due to uncertainties in the value of the STAR field we propose to use the soft iron shield in conjunction with the μ-metal.

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[13] NSPG500 green LED manufactured by Nichia Corp., Japan.

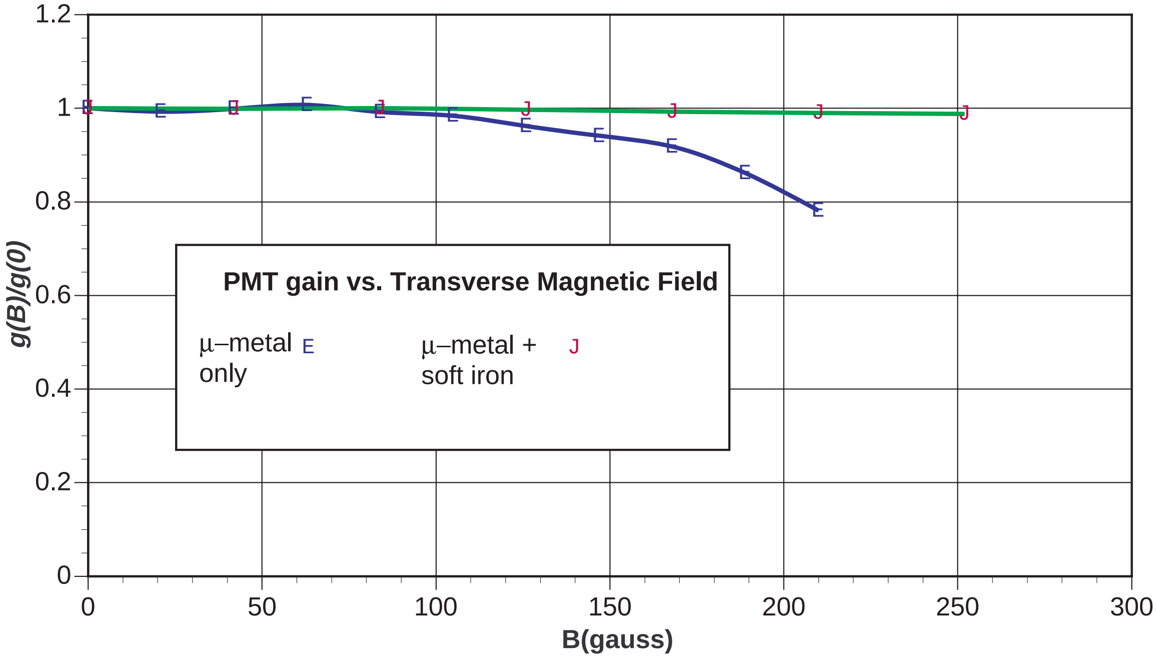

Figure 3. Magnetic shielding effectiveness of PMT assembly for transverse B field.

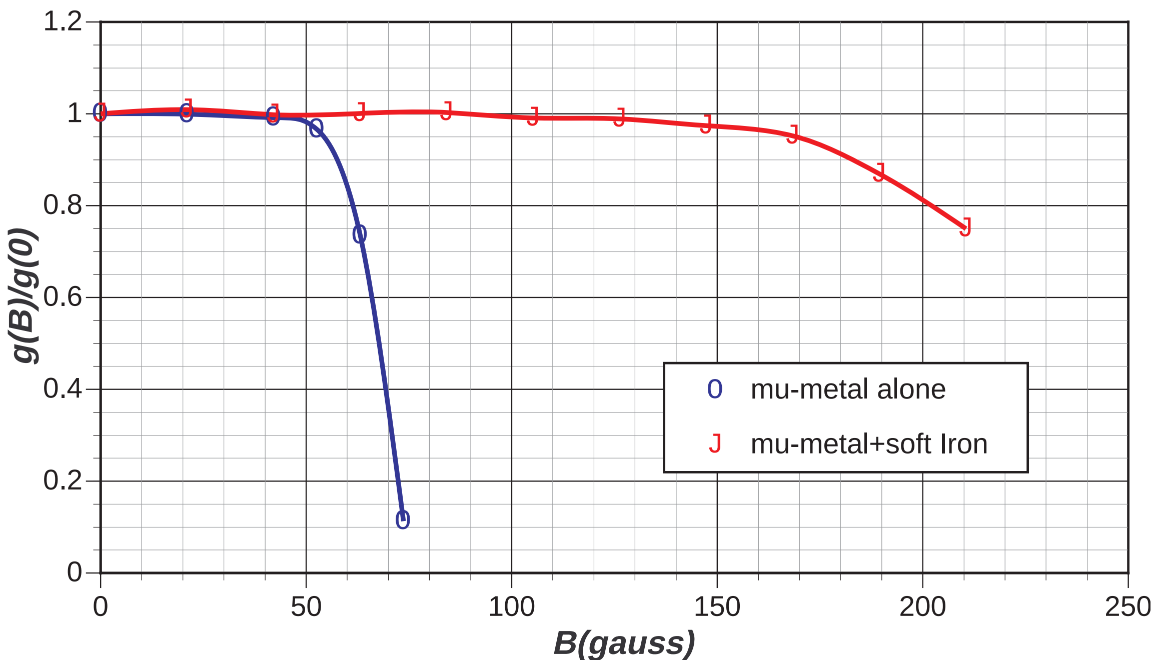

Figure 4. Magnetic shielding effectiveness of PMT assembly for longitudinal B field.

Figure 5 shows the arrangement of the PMT assemblies within the box. Note that in this arrangement there are no component of magnetic field along the PMT longitudinal axes.

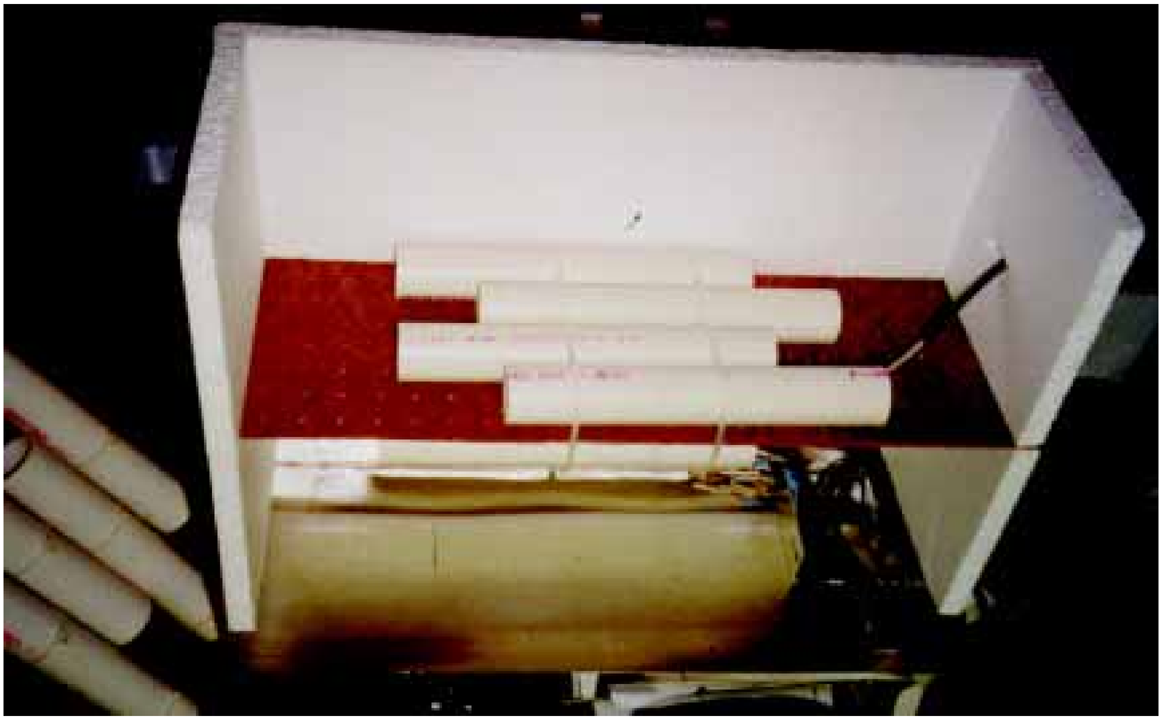

Figure 5. Arrangement of PMTs in the PMT box.

Figure 6 is a measurement of dark current as a function of HV for PMT at temperatures of 25°C and 33°C. This clearly shows that in order to maintain the dark current below 5nA one needs to operate the PMTs at the cooler temperature.

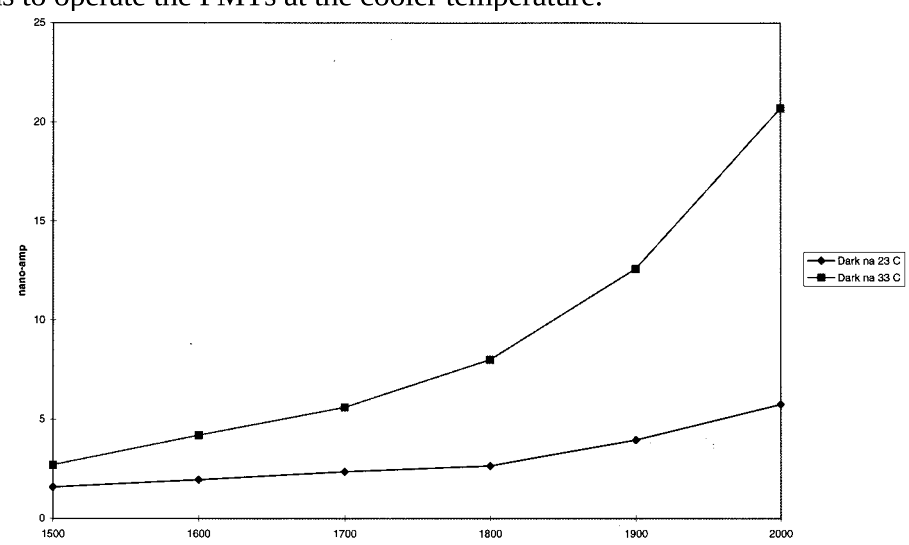

Figure 6. Measurement of FEU115U dark current.

The PMT boxes mount on the STAR backleg iron bars, and are separate from the EMC electronics crates.

The PMT boxes provide:

- Light tight environment for phototubes and fiber decoding.
- Mounting support structure for shielded PMT assemblies
- Temperature control
- Interface between fiber bundles and fiber decoding.
- Electrical shielding

In general, there are 2 boxes on each backleg, a total of 60, each handling the phototubes for 2 EMC modules from $\eta = 0$ to $\eta = 1$. There are thus 80 PMTs for towers, and 5 of the 16-channel multianode PMTs for pre-shower in each box. Each box has 1680 fibers from the calorimeter towers and 160 fibers from the preshower coming in. In addition, there are 105 internal fibers from 15 LEDs for calibration. There are 160 cables of RG174 leaving each box through 2 light-tight baffles. There are a few flat cables to provide Low Voltage and control signals to the phototubes and LED flashers. In addition, there are two water tubes of 3/8 in copper for cooling. The boxes are aluminum, with 3/4 inch styrofoam insulation inside to provide an R value of about 4.

The heat load from electronics inside a box is about 150 watts. The heat load through the walls may be in either direction, depending on the temperature of the box, the room and the magnet steel. It is calculated to be about 150 watts also. We considered using electrical heaters to stabilize the temperature to $\pm$ 1.5° F, the temperature stability that is needed for gain stability. However, the dark current goes up a factor of 4 from 23° C to 33° C, from the 2 to 4 nA range to the 8 to 16 nA range at our voltages. Thus, we are designing a heat exchanger to utilize the 60 deg F cooling water that is available. One gallon per minute of this water per box will be more than adequate.

The optical fibers from the calorimeter are arranged with fibers from 2 towers and 2 preshower towers going to 5 connectors of 10 fibers each. This wastes about 10% of the connector space, but the advantage is that there are groups of no more than 50 fibers connected by connectors on one end and PMT cookies on the other end.

Due to the constraints of the STAR magnet, there are 3 different areas with different size constraints on the PMT boxes. We have chosen to have only 2 different kinds of boxes for reasons of mass production economy.

The constraint on top of the magnet is that only 9 inches is available to clear the door when the detector rolls in. This means that electronics crates on 9 backlegs will have to be dismounted to roll the detector in and out, However, the calibration would be lost if the fiber optics were disconnected, and there would be danger of damage as well. Thus, the top boxes will be 9 inches high. The electronics crates can be mounted in such a way to allow a length of 90 inches for the top PMT boxes. The boxes are 22.5 inches wide, the same as the backleg iron, to allow access to fibers and connectors during installation, and to protect the fibers coming out the sides of the box at a steep angle (20 degrees from the box face). The cable baffles (one on each side) take up 1.5 inches at the end of the box near η=1, close to the electronic crate. There is some room between baffles for electronics for CCW control.

We can fit the phototubes into the space available in the top boxes by using 12 planes of Lucite, each carrying either 8 tower phototubes (4 on each side) or 6 tower phototubes and 1 multi-anode tube (4 tower tubes on one side and 2 on the other). The PMT shields are perpendicular to the beam direction and perpendicular to the expected magnetic field with this arrangement. The maximum diameter of the PMT shield/mounting tube is about 1.7 inches, although the CCW bases can be wider than this if oriented properly. The room for a hand and arm to access the tubes and fibers is about 3.5 inches wide by 8.25 inches deep. The fiber connectors are arranged 10 connectors of 10 fibers on each side of the box between Lucite planes.

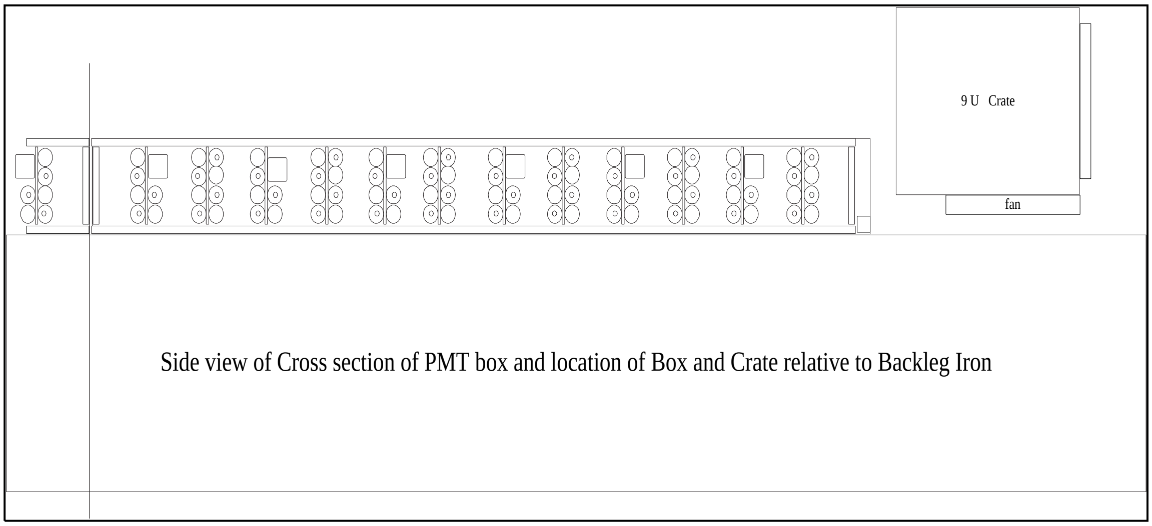

Figure 7

The constraint at the bottom of the magnet is most severe in length. The cradle for the magnet restricts the space to 66 inches and the integration of the magnet hydraulics and power further restrains the box length to 57 inches. We can fit the phototubes with the above described shields and CCW bases in by using 7 planes of Lucite, each with 7 tower phototubes on one side and 6 tower phototubes and 1 multi-anode tube on the other side. The bottom boxes are 16.5 inches in the radial direction. The room for a hand and arm to reach in for working with phototubes and fibers is about 3.5 inches wide by 15 inches deep when the sliding lid is removed.

There are other constraints at the sides of the magnet below the water hoses and power cables. Here the length is not limited, but the width of the box is limited and the radial height is limited. The boxes for the top of the magnet can be made to work here by offsetting them from the center of the backleg bar.

The electronics crates are the size of 9U VME crates. The cards pull out in the magnet axial direction, away from $\eta = 0$. In order that the cards will clear some iron blocks which are part of the magnet, the crates are mounted somewhat away from the backleg iron the top and sides of the magnet. The maximum radial distance is 21 inches. At the bottom of the magnet, there is a severe space constraint due to the magnet cradle, and some of the crates may have to be mounted outside the cradle. This affects 18 crates of 9U VME size.

V.5a Estimation of Current from PMT

First we estimate the number of photoelectrons/GeV in three ways:

1. From resolution in the test beam test of the small prototype which had 2 pe/mip/tile. The intrinsic resolution from the literature is $14\%/\sqrt{E}$. The measured resolution was $16\%/\sqrt{E}$. The derived photostatistics resolution is then $7.7\%/\sqrt{E}$, and the number of photoelectrons/GeV is then 166.

2. From the muon response in the test beam. If we get 2 pe/tile, and a muon looks like 280 MeV. Then this will be 150 pe/GeV
3. From the number of particles in a shower from formulas for shower development. At 30 GeV there are about 100 e+e- over 1.5 MeV at the peak of the shower. The distribution of the shower has an area less than half the peak height times the calorimeter depth. This gives 100 x 21 / 2 x 2 pe/mip or 70 pe/GeV if only particles over 1.5 MeV made light. The energy deposition in tiles comes from electrons down to less than 0.5 MeV, so there is a big factor more light there. I can't find the EGS calculation of this, but call it 3, so we get something like 200 pe/GeV.

To find the current from the PMT, we need the gain and the rise time. For now, say we get 1/2 the charge in the rise time of 4 ns. For a 60 GeV electron, with a PMT gain of 10^5, this gives a total of 1.2 x 10^9 electrons in the pulse, and a current of 25 ma. For a gain of 10^6, the current would be 250 ma.